Renewable and Sustainable Energy Reviews 14 (2010) 1367–1378

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Biomass conversion to energy in India—A critique

Jasvinder Singh [a,b,*], Sai Gu [a]

[a] School of Engineering Sciences, University of Southampton, Southampton SO17 1BJ, UK
[b] Indian Institute of Petroleum, Dehradun 248005, India

ARTICLE INFO

Article history:
Received 15 December 2009
Accepted 15 January 2010

Keywords:
Biomass
Bio-fuel
Agro-fuel
Algae
Gasification
Wastewater

ABSTRACT

This paper critically discusses the scope, potential and implementation of biomass conversion to energy in Indian scenario. The feasibility as well as suitability of the various categories of biomass to energy in India has been discussed. Brief descriptions of potential conversion routes have been included, with their possible and existing scope of implementation in Indian context. As far as possible, the most recent statistical data have been reported from the available sources. The figures reported have been updated as on March 2009, in most of the cases. The discussion reveals that a large potential exists for the biomass feed-stocks from the various kinds of waste biomass. The gasification as well as anaerobic digestion processes seem to be most attractive in Indian scenario.

Contents

1. Introduction . . . 1367
2. Feasibility of biomass energy conversion . . . 1368
   2.1. Environmental factors . . . 1368
   2.2. Socio-economic factors . . . 1369
3. Potential biomass availability in India . . . 1370
   3.1. Agricultural feed-stocks—energy crops . . . 1370
   3.2. Agriculture crop residues . . . 1370
   3.3. Biomass wastes—a potential feedstock for anaerobic digestion and pyrolysis . . . 1370
      3.3.1. Agro-industry wastes and leafy biomass . . . 1370
      3.3.2. Wastewaters and industrial wastes . . . 1371
      3.3.3. Food industry wastes . . . 1371
      3.3.4. Animal wastes . . . 1372
      3.3.5. Municipal solid waste . . . 1372
4. Processes for biomass conversion to energy . . . 1372
   4.1. Thermal conversion processes—liquefaction, pyrolysis and gasification . . . 1372
   4.2. Bio-chemical conversions—anaerobic digestion or fermentation . . . 1374
   4.3. Chemical transformation—bio-diesel from various sources . . . 1375
5. Conclusions . . . 1376
References . . . 1377

1. Introduction

India is a fast developing country which is achieving constant upward industrial growth in past few decades. Likewise, its commercial energy consumption is also growing with the same pace of high economic growth and industrial development. The major sources which meet the energy requirement of India are coal and oil. The primary energy consumption during 2008 are reported

* Corresponding author at: School of Engineering Sciences, University of Southampton, Southampton SO17 1BJ, UK. Tel.: +44 23 8059 8384.
E-mail addresses: jas.singh@soton.ac.uk, jsingh@iip.res.in (J. Singh), s.gu@soton.ac.uk (S. Gu).

1364-0321/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.rser.2010.01.013

to be: coal—53.4%; oil—31.2%; natural gas—8.6%; hydroelectricity—6.0%; and nuclear energy—0.8% [1]. The domestic sector consumption of energy is basically coal and kerosene. The use of these fuels is not only problematic due to emission of green house gases; these are also fast depleting sources of energy. Secondly India is dependent on the imports for oil requirements. In 2004–05, 72% of India's total oil consumption was dependent on the imports [2]. This figure reached to 76.5% during 2006–07, 78% for 2007–08, and the tentative figure for 2008–09 is 79.3% [3]. These imports are increasing year after year with the growing economy of the country and contribute in continuous increase of the import bills. In view of this, it is rather imperative on the part of researchers and energy planners, to search for alternate and renewable sources of the energy.

The major renewable sources of energy available freely are solar energy, wind energy, small hydropower, biomass, biogas, and energy recovery from municipal and industrial wastes. India is a country which is very rich in natural resources. Many of these resources have a great potential for exploitation in India. Renewable sources have advantage of complete perpetuity; easy local availability without any need for major transport, thus less green house gases release in environment; modularity, i.e. economy is independent of scale; and non-polluting in nature. The first ever attempt to exploit renewable energy in India dates back to 1897 when a small hydropower project of 130 kW capacities was implemented at Sidrapong in Darjeeling [4–6]. This was followed by two more hydro projects of 40 and 50 kW capacities respectively, each installed at Chamba (1902) and Jubaal (1911).

In the past decade there has been renewed interest in the biomass as a renewable energy source worldwide. The major reasons for this are as follows. First of all technological developments relating to the conversion, crop production, etc. promise the application of biomass at lower cost and with higher conversion efficiency than was possible previously. For example when low cost biomass residues are used for fuels, the cost of electricity is often competitive with fossil fuel-based power generation [7]. More advanced options to produce electricity are looking promising and allow a cost-effective use of energy crops e.g. production of methanol and hydrogen by means of gasification processes. In Western Europe and in the US, the second main stimulus is food surpluses producing agricultural sector. This situation has led to a policy in which land is set aside in order to reduce surpluses. In these regions, a number of factors associated with surplus land, such as the de-population of rural areas and payment of significant subsidies to keep land fallow, have provided sufficient driving force to the introduction of alternative, non-food crops desirable. The constantly rising demand for energy will provide an almost infinite market for energy crops grown on this potentially surplus land. Thirdly, the potential threat posed by climate change, due to high emission levels of greenhouse gases, the most important being CO_2, has become a major stimulus for renewable energy sources in general. When produced by sustainable means, biomass emits roughly the same amount of carbon during conversion as is taken up during plant growth. The use of biomass therefore does not contribute to a build up of CO_2 in the atmosphere.

The present paper presents a critical appraisal of the potential and scope of the bio energy production and implementation in Indian scenario. Here we have attempted to analyze the present day situation in the light of available facts and figures in the open literature. A brief description of the processes for conversion of identified biomass feedstock to energy and fuels has also been included. As far as possible, biomass availability and usage statistics has been updated to the latest figures available till date.

2. Feasibility of biomass energy conversion

In spite of many ostensible benefits, the feasibility of the biomass energy conversion especially in terms of GHG emissions is still debatable [8–10]. Avis [8] has classified the bio-energy resources into two main categories. One is agro-fuels and other bio-fuels. Bio-fuels are biomass-derived fuels designed to replace petroleum and used mainly in the transport sector. Although the words "bio-fuel" and "agro-fuel" are often used interchangeably, he emphasises to differentiate the two in order to have better assessments of their impact on the environment as well as economic analysis. An agro-fuel, is a type of bio-fuel, consisting of crops and/or trees grown on a large scale (i.e. monoculture). Examples include fuel crops such as maize, corn, oil palm, soya, sugar cane, sugar beet, oilseed rape, canola, jatropha, rice and wheat. Bio-fuels derived from waste, such as biogas from manure or landfill, or waste vegetable oil are not agro-fuels. Ethanol and bio-diesel are probably the most well known forms of agro-fuels for gasoline and diesel substitution respectively. They have been used for many years in several parts of the world.

According to this perspective, the pure plant oil, which is a bio-fuel, is sustainable when used in an integrated fashion on a farm. That is, the farmer planting the designated crops and then pressing and filtering them himself/herself to make the plant oil-fuel from it. Bio-diesel (in addition to agro-fuels such as ethanol) is usually produced on a mass-scale and marketed to conventional transportation channels, and suffers the certain drawbacks as discussed in subsequent paragraphs.

2.1. Environmental factors

The International Panel on Climate Change (IPCC) guidelines, and the World Resources Climate Analysis Data, the review produced an interesting pie-chart (Fig. 1), showing the GHG emissions by source for the year 2000. It is evident from this chart that 35% of emissions are from agriculture and changes in land-use. The land-use change is the 2nd largest source of emissions (18%), after the power sector (24%). Further, it is evident that agriculture emissions are equal (14%) and land-use change emissions are greater (18%) than the contribution from transport.

The source of agriculture emissions, due to intensive farming is nitrogen fertilizer production/utilization and emissions of nitrous oxide (NO_2) from the field. Because of the very powerful GHG effect of nitrous oxide (300 times that of CO_2) even relatively small emissions can have a significant impact on the overall GHG balance. Thus the reduction in GHG emissions basically depends on a number of things. First of all, factors such as yield, climate, soil type, and ground cover and cultivation method assumptions have a

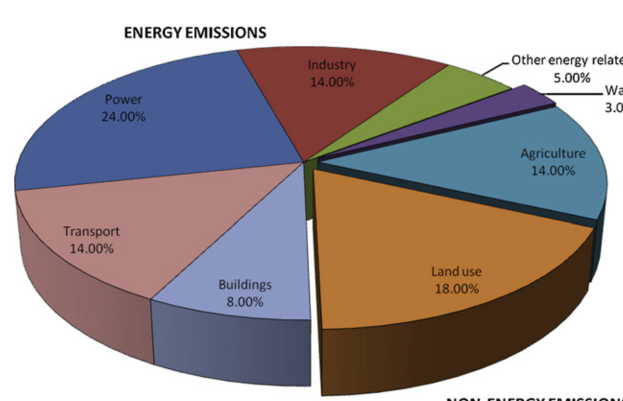

Fig. 1. GHG emissions by source for the year 2000.

very large affect on estimated emissions. Secondly, base case assumptions such as the original land-use and whether deforestation occur to make room for the fuel crop. Third important factor is process to make the fuel. In the case of ethanol production, the use of cogeneration with a gas-fired turbine over conventional production schemes has been claimed to reduce GHG emissions by 45% [8]. However, using coal would wipe out the GHG savings as compared to gasoline. By-product usage is another important factor. It makes a difference if the by-products of the distillation process used as animal feed or for fuel. The lowest overall GHG emissions (up to 80% reduction over fossil fuels) are attainable when bio-diesel is made from waste cooking oil or methane from liquid manure.

In view of the above the implementation of bio-fuels in any country, the environmental impact is the major factor to be considered before we consider the exploitation of bio-energy. As mentioned in the last paragraph, the land-use change is the major contributor to the GHG emissions. These considerations are necessary at the time of making life cycle assessment of any bio-energy generation process.

2.2. Socio-economic factors

The Bio energy Wiki [9] contains information on renewable fuel targets for various countries. According to it, India target to achieve 5% in ethanol in certain states and 20% bio-diesel by the year 2012. But the reported fact [10] on the experiences of Chattisgarh State, is that 400 million Jatropha saplings were planted on more than 155,000 ha of fallow land in the last 3 years. However, until end of the year 2008, there has been no reported data on survival of saplings or seed production. Farmers in many areas are in a fix as the trees have not yet borne fruits, while in places where they have, various departments and local agencies, and are waiting for guidelines on collection and sale of seeds. Similarly, a 2006 analysis by the UN Conference on Trade and Development (UNCTAD) concluded that India cannot rely on sugarcane molasses as a reliable feedstock for alcohol, given the crop's dependence on monsoon and vagaries of the domestic sugar industry. Similarly, difficulties in procuring oilseeds and lack of infrastructure could obstruct substantial bio-diesel production by 2011–12.

While considering the utilization of agro-fuels, the social impacts are also important and cannot be overlooked due to many reasons. In the process of implementing bio-fuels, particularly agro-fuels, we need to ensure that the land as well as resources, we are allocating to the harvesting of these crops do not interfere the food crops sector. Secondly, in this process lest we make some of the farmers jobless. In a country like India agriculture is one of the most important sectors of its economy. It is the means of livelihood of almost two thirds of the work force in the country and according to the economic data for the financial year 2006–07, agriculture accounts for 18% of India's GDP. About 43% of India's geographical area is used for agricultural activity. Though the share of Indian agriculture in the GDP has steadily declined, it is still the single largest contributor to the GDP and plays a vital role in the overall socio-economic development of India. The poor farmers, not only earn their livelihood, but the food for their family is also coming from their crops.

It is claimed very often that Jatropha plants do not need any irrigation and poor farmers can grow it without irrigation on poor soils. But some studies carried out in India [11] as well as in the other parts of the world [12–16] show that the average yield of the seeds after 5 years, without irrigation is 1.1–2.75 t/ha as compared to 5.25–12.5 t/ha with irrigation. In view of this if we need to grow it at commercial scale for production of bio-diesel, Jatropha plantation is certainly going to compete with the food crops. Just by cultivating it on the marginal lands, its production may not come up to commercial scale or may be economically unviable. So in these circumstances sooner or later, the agro-fuel promotional drive is going to compete with the food crops. If it happens then in India also, the story of the farmers may not be different than one quoted by Michelle Avis of an Afro-Columbian Woman, "In her village in El-Choco, she had no need for employment, as she had access to the necessary resources. Her family shared a communal plot of land where they grew their food. When bio-crop enthusiasts arrived in her village she and her husband and children were forced from their land. They now live in a slum of Bagotá where they have no access to their land on which to grow food on."

The solution of the problems is being explored in production of bio-diesel from another biomass, i.e. algae [17–19]. The viability of microalgae for bio-diesel production has been studied by a number of authors. A comprehensive review on it has been presented by Mata Teresa et al. [20]. Microalgae are eukaryotic photosynthetic microorganisms that can grow rapidly and live in harsh conditions due to their unicellular or simple multi-cellular structure. Some of the known prokaryotic microorganisms are cyanobacteria (Cyanophyceae) and eukaryotic microalgae are for example green algae (Chlorophyta) and diatoms (Bacillariophyta) [21,22]. Richmond [23] has described about microalgae in more depth in his paper. Microalgae are present in all existing earth ecosystems, not just aquatic but also terrestrial, representing a big variety of species living in a wide range of environmental conditions. It is estimated that more than 50,000 species exist, but only a limited number, of around 30,000, have been studied and analyzed [23]. During the past decades extensive collections of microalgae have been created by researchers in different countries. An example is the freshwater microalgae collection of University of Coimbra (Portugal) considered one of the world's largest, having more than 4000 strains and 1000 species. This collection attests to the large variety of different microalgae available to be selected for use in a broad diversity of applications, such as value added products for pharmaceutical purposes, food crops for human consumption and as energy source.

A bit all over the world, other algae collections attest for the interest that algae have risen, for many different production purposes. For example, the collection of the Goettingen University, Germany (SAG), that started in the early 1920s and has about 2213 strains and 1273 species [20]. About 77% of all the strains in the SAG collection are green algae and about 8% cyanobacteria (61 genera and 230 strains). Some of them are freshwater red algae and others from saline environments. The University of Texas Algal Culture Collection is another very well known collection of algae cultures that was founded in 1953. It includes 2300 different strains of freshwater algae (edaphic green algae and cyanobacteria), but includes representatives of most major algal taxa, including many marine macrophytic green and red algae species. In the Asian continent, the National Institute for Environmental Studies Collection (NIES), in Ibaraki, Japan, holds a collection of about 2150 strains, with around 700 species of different algae. The CSIRO Collection of Living Microalgae (CCLM), in Australia, holds about 800 strains of different algae, including representatives from the majority of classes of marine and some freshwater microalgae, being the majority of the strains isolated from Australian waters [20].

Apart from the first generation bio-fuels derived from bio-crops, now second generation bio-fuels are gaining interest of the scientists and engineers. These non-plantation feed-stocks include agriculture residues, wood processing residues, municipal solid waste (MSW), livestock dung, landfill gases, etc. As mentioned above a large population of India is based mainly on agriculture. Therefore a reasonable amount of agriculture residue as well as livestock dung is produced every year. In India, biomass fuels dominate the rural energy consumption patterns, accounting for over 80% of total energy consumed [24]. Fuel wood, crop residues

(including plantation crops) and livestock dung are the biomass fuels used in rural areas. Fuel wood is the preferred and most dominant biomass source accounting for 54% of bio-fuels used in India [25]. Scarcity and increasing prices of fuel wood have been altering the bio-fuel consumption pattern. Due to scarcity of fuel wood, people are shifting to dung and various crop residues. The use of bio-fuels in domestic devices is associated with drudgery and adverse health impacts on women [26]. In most rural houses, the fuel use efficiency in domestic devices, particularly cook stoves, is low, in the range of 10–14% [27]. Thus, improving the conversion efficiency would be a significant step towards improving the quality of life and environment. Efforts are already under way to promote efficient devices and alternate energy sources for improving the quality of life and conserving biomass resources.

3. Potential biomass availability in India

Biomass, defined as all land and water-based vegetation as well as organic wastes, fulfilled almost all of human kind's energy need prior to the industrial revolution. In present day scenario, once again its utilization for generation of energy has gained momentum because of limited availability of the conventional energy resources as well as environmental concern due to GHG emissions [28]. Researchers characterize the various types of biomass in different ways, but one simple classification is as follows. The main types of biomass are woody plants, herbaceous plants or grasses/shrubs, aquatic plants, and manures. Recently algae have also been identified as a potential source of bio-diesel. Basically there are three distinct sources of biomass energy: energy plantations, agricultural crop residue and municipal and industrial wastes. A brief description about all of these has been given in the following subsections.

3.1. Agricultural feed-stocks—energy crops

A large population in India is dependent on agriculture as their livelihood. In view of this a large population of cattle and livestock also exists in India. Therefore the potential of various kinds of biomass availability exists in Indian villages [29,30]. Crops that have been used for energy include: sugarcane, corn, sugar beets, grains and many others. There are several factors, which determine whether a crop is suitable for energy use. The main material properties of interest during subsequent processing as an energy source, relate to—moisture content (intrinsic and extrinsic), calorific value, proportions of fixed carbon and volatiles, ash/residue content, alkali metal content, and cellulose/lignin ratio. The first five properties are significant for dry biomass conversion processes, while first and last properties are important for wet biomass conversion [7]. Good energy crops have a very high yield of dry material per unit of land (dry ton/ha). A number of authors have also estimated the potential land for growing biomass in India. Table 1 presents an overview of the findings of these authors. These studies are based on FAO statistical data as well as other sources of agriculture statistics in terms of most of the Indian biomass feed-stocks [31–35].

Table 1
Available potential land for biomass production in India reported by different authors/sources.

Author/data source	Land category	Estimated available area (Mha)
Planning Commission data [31]	Degraded forest	36
	Degraded non-forest (total)	94
	Degraded non-forest (land available for tree plantation)	
	Cultivated land	13
	Strips and boundaries	2
	Uncultivated land	33
Kapoor (1992) [32]	Land available for tree plantation	
	Agricultural land	45
	Forest land	28
	Pasture Land	7
	Fallow land (long and short)	25
	Urban land	1
Handbook of Statistics: Section A (1996–97), Table 03 (Ministry of Agriculture, India) [33]	Forests	68.75
	Non-agricultural uses land	22.45
	Barren land	19.09
	Permanent pasture land	11.04
	Tree crops and grooves	3.57
	Culturable waste land	13.94
	Old fallow land	9.89
	New fallow land	13.33
Sudha (1996) [34]	Cultivable land under agro ecological zones	26.1
	Land unsuitable for cultivation	13.6
	Pasture land	2.9
NRSA (1995) [35]	Forest degraded land	16.27
	Waste land	38.11
	Other category	11.07

3.2. Agriculture crop residues

A large amount of agriculture residues are produced in agriculture based country like India. These constitute a potential biomass feedstock for energy conversion. The term agricultural residue is used to describe all the organic materials which are produced as the by-products from harvesting and processing of agricultural crops. These residues can be further categorized into primary residues and secondary residues. Agricultural residues, which are generated in the field at the time of harvest are defined as primary or field based residues (e.g. rice straw, sugar cane tops), whereas those co-produced during processing are called secondary or processing based residues (e.g. rice husk and bagasse). Availability of primary residues for energy application is usually low since collection is difficult and they have other uses as fertilizer, animal feed, etc. However secondary residues are usually available in relatively large quantities at the processing site and may be used as captive energy source for the same processing plant involving no or little transportation and handling cost. In order to assess the potential of primary residues, the available data has been listed in Table 2 [36–38]. This table lists the potential Indian crops generating residues and their available quantity.

3.3. Biomass wastes—a potential feedstock for anaerobic digestion and pyrolysis

A huge quantity of various biomass wastes are generated in developing countries like India. These wastes can be converted to the energy fuels by bio-chemical as well as thermo-chemical conversion routes. The potential biomass wastes identified and used for bio-energy production in India are listed in the subsequent subsection. Many of these wastes are being successfully utilized in various bio energy applications across the country.

3.3.1. Agro-industry wastes and leafy biomass

Apart from the residues from the agricultural farms and fields in urban areas certain other residues and wastes also constitute a potential source of the energy. The agro processing industries, urban vegetable market places, road sweepings and road side plantations are some areas which generate significant biomass

Table 2
Production of different crops and their respective residue availability in India.

S.N.	Name of the crop	Annual production, thousand M T	Type of residue	Crop to residue ratio, residue/kg crop	Total available residue, thousand M T
1	Areca nut	330	Fronds	3[a]	0.857
			Husks	0.8	264
2	Arhar (tur)	1,950	Husks	0.3	585.3
			Stalks	2.5	4,875
3	Bajra	7,690	Cobs	0.33	2,537.7
			Husks	0.3	2307
			Stalks	2	15,380
4	Banana	80,000	Residue	3	240,000
5	Barley	1,200	Stalks	1.3	1,560
6	Cardamom	8.5	Stalks	0.64[a]	0.04687
7	Coconut	13,125.2	Fronds	4[a]	7.6
			Husk and pith	0.53	6,956.356
			Shell	0.22	2,887.544
8	Coffee	300.3	Husk	0.5	150.15
			Pruning and wastes	4[a]	1.328
9	Coriander	250	Stalks	1.15	287.5
10	Cotton	3,000	Boll shell	1.1	3,300
			Husk	1.1	3,300
			Stalks	3.8[a]	34.922
11	Cumin Seed	200	Stalks	1.55	310
12	Dry Chilly	800.1	Stalks	1.5	1,200.15
13	Ginger	273.333	Stalks	0.05	13.667
14	Garlic	598	Sheath	0.25	149.5
			Stalks	0.05	29.9
15	Rice	145,050	Husks	0.2	29,010
			Stalks	1.5	217,575
			Straw	1.5	217,575
16	Sugarcane	276,250	Bagasse	0.33	91,162.5
			Top and leaves	0.05	13,812.5
17	Wheat	78,000	Pod	0.3	23,400
			Stalks	1.5	117,000
18	Maize	18,500	Cobs	0.3	5,550
			Stalks	2	37,000
19	Cassava	6,060	Solid waste	0.6	3,636
			Starch from roots	1.2	10,908
20	Millets	12,410	Stalks	1.2	14,892
21	Urad dal	750	Husk	0.2	150
			Stalks	1.1	825
22	Rubber	825	Primary wood	3[a]	1.743
			Secondary wood	2[a]	1.162

[a] Tonnes/hectare.

waste. The management of these areas is generally in the hands of poor farmers and the unorganized sector, rural households and the low income tiny agro based industry sector. A recent report [39] shows that almost 200 million tonnes of household and agro processing wastes are generated annually in India and disposed in a dispersed manner. Since they are associated with little or no production costs they are either unused or utilized inefficiently. Large amounts of leafy wastes are burnt resulting in air pollution.

3.3.2. *Wastewaters and industrial wastes*

Effluents and other wastes create problems of water and soil pollution. Dumping has serious consequences. During the process of organic decomposition of these wastes on land, organic matter percolates into the ground water or runs off to surface waters causing pollution which leads to health hazards and fish mortality. These are waste effluents from the industries such as black liquor from pulp and paper industry, wastewater from slaughterhouse, milk processing units, breweries, vegetable packaging industry, and animal manure. Table 3 shows the potential industries producing wastewater for the anaerobic digestion and their energy potential. The wastewater production figures in India and typical COD have been taken from the various sources in literature [25,40]. The energy production potential may depend upon the reactor being used and reactor efficiency [41,42], but these wastes can effectively be used as feedstock for the bio-fuel production. The biogas production potential has been reported by various authors in the range of 0.15–0.45 m^3 CH_4/kg of COD removed [42]. The figures reported for energy potential in this table are calculated on a basis of an average value of 0.3 m^3 CH_4/kg.

3.3.3. *Food industry wastes*

The hotel, restaurants and community kitchens produce a lot of waste such as vegetable peels, uneaten food e.g. rice, bread, vegetables, meat, etc., plate and dish washings, fruit and vegetable rejects. Similarly, a huge amount of wastes are generated from confectionary industry.

Solid wastes from these industries include peelings and scraps from fruit and vegetables, food that does not meet quality control standards, pulp and fibre from sugar and starch extraction, filter sludges and coffee grounds. All these wastes make a potential feedstock for biogas generation by anaerobic digestion [39]. These wastes are usually disposed off in landfill dumps [43].

Liquid wastes are generated by washing meat, fruit and vegetables, blanching fruit and vegetables, pre-cooking meats, poultry and fish, cleaning and processing operations and wine making [44]. These wastewaters contain sugars, starches and other dissolved and solid organic matter. The potential exists for these industrial wastes to be anaerobically digested to produce biogas, or fermented to produce ethanol. Several commercial examples of waste-to-energy conversion already exist using these feed-stocks.

Table 3
Energy potential of wastewater in India.

Industry	Wastewater produced (Mm^3)	COD of wastewater (kg/m^3)	Energy value of CH_4 at 20% conversion of wastewater to energy, TJ (Note 1,2)	Energy value of CH_4 at 90% conversion of wastewater to energy, TJ (Note 2)
Distillery	6,000	118.00	5,947.20	9,558.00
Steel plants	1,040,000	0.60	5,241.60	8,424.00
Paper and pulp	7,200	5.91	357.44	574.45
Sugar industry	230	2.50	4.83	7.76
Cotton	1,550	0.60	7.81	12.56
Fertilizers	52	2.00	0.87	1.40
Refineries	15	0.30	0.04	0.06
Dairy	206	2.24	3.88	6.23
Pharmaceuticals	56	0.39	0.18	0.29
Coffee	1.3	2.80	0.03	0.05
Edible oil	1,425	4.60	55.06	88.49
Total	1,056,730		11,618.94	18,673.30

Data sources: [25,41,42].
Notes: 1. The IPCC default value of 20% is considered as the fraction of wastewater treated in anaerobic systems. For distillery 56% is considered based on literature data [25].
2. It is assumed that with advent of efficient waste treatment mechanisms and innovations in reactors, up to 90% of wastewater can be treated in an anaerobic system.
3. Energy values are calculated with a conversion factor of 0.05 MJ/m^3 CH_4, with methane producing capacity of 0.30 m^3 CH_4/kg COD.

3.3.4. Animal wastes

Animal manure is principally composed of organic material, moisture and ash. Decomposition of animal manure can occur either in an aerobic or anaerobic environment. Under aerobic conditions, CO_2 and stabilized organic materials (SOM) are produced [44]. Under anaerobic conditions, CH_4, CO_2, and SOM are produced. Since the quantity of animal manure produced annually can be substantial for a country like India, the potential for CH_4 production and hence energy potential of animal manure is significant.

3.3.5. Municipal solid waste

Millions of tonnes of household waste are collected each year with the vast majority disposed off in open fields. The biomass resource in MSW comprises the paper and plastic and averages 80% of the total MSW collected. Municipal solid waste can be converted into energy by direct combustion, or by natural anaerobic digestion in the engineered landfill.

On the landfill sites the gas produced by the natural decomposition of MSW (approximately 50% methane and 50% carbon dioxide) is collected from the stored material and scrubbed and cleaned before feeding into internal combustion engines or gas turbines to generate heat and power [44]. The organic fraction of MSW can be anaerobically stabilized in a high-rate digester to obtain biogas for electricity or steam generation.

Sewage is a source of biomass energy that is very similar to the other animal wastes. Energy can be extracted from sewage using anaerobic digestion to produce biogas. The sewage sludge that remains can be incinerated or undergo pyrolysis to produce more biogas.

Table 4 shows a compilation of data regarding some of the existing agencies and/or industries practicing the conversion of different waste biomass to energy in India and reported benefits from these. This clearly depicts the enormous potential of conversion of various biomass wastes to energy, in Indian scenario. Many of these technologies have profitably been implemented and are being used by industries by in-house energy saving, and thus adding up to their profits. These technologies are being adapted by similar industries with the help of various government agencies e.g. MNRE (formerly known as MNES), academic institutions like Indian Institute of Science (IISc) and Indian Institutes of Technology (IITs), as well as certain non-government organisations.

The above discussion and compiled data clearly implies that large scope exists for the exploitation of bio-crops for their conversion to bio-fuels e.g. ethanol and bio-diesel, by thermo conversion as well as bio-chemical conversion routes. Apart from these energy crops, a huge potential exists for energy generation from the various industrial wastewaters by bio-chemical routes. Similarly other biomass wastes e.g. wood wastes, crop residues, animal manures, and municipal wastes also bear a large potential for energy generation using bio-chemical as well as thermo-chemical routes. Thus biomass conversion to energy and fuels may be a quite rewarding in Indian scenario.

4. Processes for biomass conversion to energy

It is evident from the above discussion that a variety of feedstocks are available for exploitation for conversion to the bio-fuels as well as for power generation applications. In view of this a variety of processes exists for biomass conversions. The most used of these are thermal conversions, bio-chemical and chemical conversions and direct combustion. The thermal conversion processes consist of fast and slow pyrolysis and biomass gasification; the bio-chemical conversion is fermentation and anaerobic digestion; chemical conversions are trans-esterification and other processes to convert plant and vegetable oils to bio-diesel, and direct combustion of wood and other biomass is being used for a very long. This subsection presents a critical review of these known processes in Indian scenario.

4.1. Thermal conversion processes—liquefaction, pyrolysis and gasification

The main thermal conversion processes known for biomass conversion are liquefaction, slow and fast pyrolysis, and gasification. The chemical composition of biomass is very different from that of coal oil, oil shales, etc. The presence of large amounts of oxygen in plant carbohydrate polymers means the pyrolytic chemistry differs sharply from these other fossil feeds. Wood and other plant biomass is essentially a composite material constructed from oxygen-containing organic polymers. The plant biomasses mainly consist of low molecular weight organic extractives and inorganic minerals (usually 4–10%), and Macromolecules like polysaccharides e.g. cellulose and polyoses (usually 65–75%) and lignin (around 18–35%) [45]. The species undergoing chemical change during thermal conversion are cellulose, hemicelluloses, and lignin. The wt percent of these components vary in different varieties of woody biomass. Various biomass feeds transform to bio-oil and char to various extents, depending upon their chemical composition as well as moisture contents. Pyrolysis is the fundamental chemical reaction process that is the precursor

Table 4
Conversion of different waste biomass to energy in India and reported benefits.

S.N.	Name of the industry/agency	Feedstock/waste	Conversion route	Applications	Reported benefits/savings
1.	Sakthi Sugars, Maharashtra	Sugarcane bagasse	Biomethanation	Heating	Reported IRR = 32% Biogas substituted for almost 87% of fuel oil consumption
2.	K.M. Sugar Mills, Uttar Pradesh	Do	Do	Power plant (capacity 1 MW)	12,000 m^3 biogas produced from 400 KL of spent wash per day
3.	Pravar Nagar, Sugar factory at Maharashtra	Sugar factory press mud (75% organic matter; 29% solid content; 65% is volatile)	Biogas (having 60% methane)	Domestic fuel for cooking	Four biogas plants each having 85 m^3 capacity each are setup with MNES financial assistance. Meeting cooking needs of 196 households for 4 h per day
4.	Demo plants by an NGO—Appropriate Technology Institute (ARTI)	Sugarcane leaves left after harvesting	Oven and rotary kiln conversion to char and briquetting	Fuel for various applications	Plant output 100 kg char per day. Earning of Rs. 75,000 in 25 weeks of harvesting season
5.	ASTRA, IISc	Leafy biomass	Biogas	Fuel	It is claimed that 2/3 of the families of estimated 100 million rural household could be provided if we use only 10% of around 1130 million ton leafy biomass waste available in India
6.	Al-Kabeer Exports Pvt. Ltd., Medak (Andhra Pradesh)	Slaughter house waste (liquid and solid)	Two stage digestion process for Biogas production	Fuel	3000–4000 m^3 gas is produced, which saves furnace oil consumption worth Rs. 4 million per annum
7.	Western Hatcheries Ltd.	Poultry waste	UASB reactor for biogas production	Power plant (capacity 1.2 MW)	60 m^3 biogas is produced per day from 200 TPD poultry waste processing plant at Namakhal
8.	MSW to energy & resources in Singupa town in Bellary District by Technology Informatics design Endeavour (TIDE) & IISc	Organic fraction of municipal waste	Plug flow biogas reactor	Not known	Data collected shows that 1 kg waste gives 50–60 l of biogas. C/N ratio of compost is found to be 11.4
9.	Coffee Board and Ministry of Commerce	Coffee pulping waste	Bioreactor for biogas conversion	Power generation	About 80 m^3 of biogas is produced from each ton of coffee parchment. The technology has been successfully demonstrated at 13 locations
10.	Transport House, KSRTC, Bangalore	Canteen waste (rice straw, bagasse, paper shreds, garden cuttings, lawn mowing, vegetable peels, uneaten rice, plate and dish washings, fruit and vegetable rejects)	Biomethanation	Fuel for food warming	The KSRTC plant can handle 25 kg of canteen rejects per day along with leaf litter, which produces 1.5 m^3 of biogas
11.	TERI's Gurgaon campus at Gual Pahari	Fibrous and semi-solid organic wastes	Acidification and methanation process (biogas containing 70–75% methane, rest CO_2, and traces of H_2S and moisture)	Various uses	TERI claims it to be a useful way to turn wastes from food and fruit processing industries, hotels, pilgrim houses, hostels, housing colonies, community kitchens, vegetable markets, etc.

of both the gasification and combustion of solid fuels. In simple terms pyrolysis is defined as the chemical changes occurring when heat is applied to a material in the absence of oxygen. Combustion of biomass for use in internal combustion engines for power generation provides an important alternate renewable energy resource. Gasification is partial combustion of biomass to produce gas and char at the first stage and subsequent reduction of the product gases, chiefly CO_2 and H_2O, by the charcoal into CO and H_2. The process also generates some methane and other higher hydrocarbons depending on the design and operating conditions of the reactor [46]. Various pyrolysis processes have been briefly described in the following subsections.

As mentioned above, conventional pyrolysis is defined as the pyrolysis, which occurs under a slow heating rate. This condition permits the production of solid, liquid, and gaseous pyrolysis products in significant portions [47]. Conventional slow pyrolysis has been applied for thousands of years and has been mainly used for the production of charcoal. The heating rate in conventional pyrolysis is typically much slower than that used in fast pyrolysis. A feedstock can be held at constant temperature or slowly heated. Vapours can be continuously removed as they are formed [48].

Slow pyrolysis of biomass is associated with high charcoal continent, but the fast pyrolysis is associated with tar, at low temperature (675–775 K), and/or gas, at high temperature. At present, the preferred technology is fast or flash pyrolysis at high temperatures with very short residence times [49].

Fast pyrolysis (more accurately defined as thermolysis) is a process in which a material, such as biomass, is rapidly heated to high temperatures in the absence of oxygen [49].

Flash pyrolysis of biomass is the thermo-chemical process that converts small dried biomass particles into a liquid fuel (bio-oil or bio-crude) for almost 75%, and char and non-condensable gases by heating the biomass to 775 K in the absence of oxygen. Char in the vapour phase catalyzes secondary cracking. Table 5 shows the range of the main operating parameters for pyrolysis processes [50].

Table 5
Main operating parameters for pyrolysis processes.

Parameter	Conventional pyrolysis	Fast pyrolysis	Flash pyrolysis
Pyrolysis temperature (K)	550–900	850–1250	1050–1300
Heating rate (K/s)	0.01–1	10–200	>1000
Particle size (mm)	5–50	<1	<0.2
Solid residence time (s)	300–3600	0.5-10	<0.5

The biomass pyrolysis is an attractive option because solid biomass and wastes can be readily converted into liquid products. These liquids, as crude bio-oil or slurry of char of water or oil, have advantages in transport, storage, combustion, retrofitting and flexibility in production and marketing. Rapid heating and rapid quenching produced the intermediate pyrolysis liquid products, which condense before further reactions break down higher-molecular-weight species into gaseous products. High reaction rates minimize char formation. At higher fast pyrolysis temperatures, the major product is gas. If the purpose is to maximize the yield of liquid products resulting from biomass pyrolysis, low temperature, high heating rate, short gas residence time process would be required. For a high char production, a low temperature, low heating rate process would be chosen. If the purpose were to maximize the yield of fuel gas resulting from pyrolysis, a high temperature, low heating rate, long gas residence time process would be preferred [49,50]. Table 6 shows the typical yields of char, liquid and gas from the various biomass pyrolysis options [50].

Biomass pyrolysis finds a direct application in power generation application in Indian scenario. A conventional route for power generation from biomass, being practiced in India is direct combustion of biomass to generate steam to run the turbines [51]. The recent efforts to improve upon the efficiencies and to reduce the operating costs, led to the development of the gasifiers on the conversion side, and use the combined cycle and engines on the gasification side. The pyrolysis has emerged out another efficient route for conversion of biomass to liquids gases, and char with liquids being the main target. Power generation using this technology is essentially by the use of pyrolysis oils for gas turbine integrated into a combined cycle.

Biomass energy and cogeneration programme is being implemented with the main objective of promoting technologies for optimum use of country's biomass resources and the exploitation of the biomass power generation potential, estimated at 25,000 MW as per MNES annual report for 2008–09. During the year, biomass power/bagasse cogeneration capacity addition of 345 MW (97 MW biomass projects and 248 MW bagasse cogeneration projects) was achieved in the States of Andhra Pradesh, Chhattisgarh, Karnataka, Maharashtra, Rajasthan, Tamil Nadu and Uttar Pradesh against a target of 300 MW. The cumulative biomass power/bagasse cogeneration based power capacity has reached 1752 MW, which comprises 703 MW of biomass power projects and 1049 MW of bagasse cogeneration projects. The details of biomass and cogeneration energy capacity installed in different states of India are given in Table 7.

Some of the cogeneration projects have been reported by authors is in Southern and Eastern parts of India [52]. Biomass gasification electricity generation has been installed for both mini-grid rural electrification and supply for main grid. There is 1 MW capacity of 100% producer gas based grid connected power generation was commissioned in December 2004. This is operated by Arashi Hi-Tech Bio-Power Pvt. Ltd. in Coimbatore, Tamil Nadu State as independent power producer (IPP). They started the operation in 2002 using duel fuel engines but engines are replaced with 4× 250 kW Cummins producer gas engines and an additional gasifier. Currently Juliflora (*Prosopis juliflora*) wood is used as the feedstock and the system has already been operated over 4000 h. Juliflora is very common legume woody weed in the state. There are many various sizes of biomass gasifier rural electrification scheme commissioned. Gosaba Island project [53] is the oldest relatively large scale (500 kW) scheme and has been operating since 1997. The 4× 250 kW (1 MW) installation in Khtrichera, Tripura State would be the largest biomass gasifier rural electrification project. Subsidies for rural electrification subsidy for biomass gasification rural electrification varies depending on the plant capacity, ownership and location. In case of rural electrification owned by community, up to 90% of total initial cost would be supported by national government and the rest can be met by community or rural government.

4.2. Bio-chemical conversions—anaerobic digestion or fermentation

The process of bio-chemical conversion of biomass carried out by alcoholic fermentation to produce liquid fuels and anaerobic digestion or fermentation, for producing biogas. High moisture herbaceous plants (vegetables, sugar cane, sugar beet, corn,

Table 6
Char liquid and gas percent yields from plant biomass by pyrolysis and gasification.

Thermal degradation	Residence time (s)	Upper Temp (K)	Char	Liquid	Gas
Conventional pyrolysis	1800	470	85–91	7–12	2–5
	1200	500	58–65	17–24	8–14
	900	550	44–49	26–30	16–22
	600	600	36–42	27–31	23–29
	600	650	32–38	28–33	27–34
	600	850	27–33	20–26	36–41
	450	950	25–31	12–17	48–54
Slow pyrolysis	200	600	32–38	28–32	25–29
	180	650	30–35	29–34	27–32
	120	700	29–33	30–35	32–36
	90	750	26–32	27–34	33–37
	60	850	24–30	26–32	35–43
	30	950	22–28	23–29	40–48
Fast pyrolysis	5	650	29–34	46–53	11–15
	5	700	22–27	53–59	12–16
	4	750	17–23	58–64	13–18
	3	800	14–19	65–72	14–20
	2	850	11–17	68–76	15–21
	1	950	9–13	64–71	17–24
Gasification	1800	1250	7–11	4–7	82–89

Table 7
Power generation by biomass power installations in various states of India.

S.N.	Programme/process	Total cumulative power generation as on 31.03.2009
1.	Biomass (agro-residue and plantation)	703.3 MW
2.	Cogeneration (bagasse)	1048.73 MW
3.	Cogeneration (non-bagasse)	170.78 MW
4.	Biomass gasifier	242.9 MWeq.
5.	Energy recovery from waste	34.06 MWeq.

Source: MNES Annual Report 2008–09.

sorghum, and cotton) marine crops and manure are most suitable for anaerobic digestion. Intermediate-heat gas is methane mixed with CO and CO_2. Methane (high-heat gas) can be efficiently converted into methanol. Biogas has emerged as an important component of the renewable energy programmes of several developing countries. However, the spread of biogas technology has not been commensurate with its potential.

Chanakya et al. [54] has reviewed the biomethanation of herbaceous biomass feedstock as a potential source of clean energy source in Indian scenario for cooking and other activities in areas where such biomass availability predominates. A biomethanation concept that involves fermentation of biomass residues in three steps, occurring in three zones of the fermentor has been described. According to them, India has built about 4 million family sized biogas plants in the past (out of the possible 12 million) that operate largely with animal excreta as the sole feedstock [55,56]. There are about 100 million rural families in India. The goal of providing clean cooking energy [57,58] to the large rural population through biogas technology can only be met by using non-dung biomass feed-stocks as alternative feed-stocks. Towards this quest a large number of laboratory and pilot plant studies have been carried out at different places in India to convert various biomass feed-stocks to biogas, notably with water weeds [59] such as water hyacinth (Eichhornia sp.) and Salvinia. The approach had been simple—to pulverize these feed-stocks into small particles and render them into a water-based slurry [60] and finally feed them to conventional animal-waste-type biogas plants. Similar efforts have been made with kitchen-wastes [61], crop residues such as rice straw [62], terrestrial weeds [63,64], aquatic weeds [65], green algae, etc.

Crushed water hyacinth when fed to a typical floating drum-type biogas plant was found to segregate into three clear zones [66–69]. Chanakya et al. [54], 2009 have reported that over 85% of the material fed to the 12 m^3 plant remained afloat as a scum. This floating scum occupied gas storage space under the floating gas-holder. A clearly large liquid zone remained as an intermediate layer occupying 80% of digester space while a small layer of sludge settled down. No digested matter came out of the outlet after 180 d operation. This approach while attempting take advantage of multistage reactors simplifies the reactor operation and obviates the need for a high degree of process control or complex reactor design. Decomposing herbaceous biomass releases large quantities of intermediate volatile fatty acids (VFA) which tend to accumulate and inhibit methanogenesis. Typical herbaceous biomass decompose with a rapid VFA flux initially (with a tendency to float) followed by a slower decomposition showing balanced process of VFA generation and its utilization by methanogens that colonize biomass slowly. The tendency to float at the initial stages is suppressed by allowing previous days feed to hold it below digester liquid which permits VFA to disperse into the digester liquid without causing process inhibition.

This approach has been used to build and operate simple biomass digesters to provide cooking gas in rural areas with weed and agro-residues. With appropriate modifications, the same concept has been used for digesting municipal solid wastes in small towns where large fermentors are not viable. With further modifications this concept has been used for solid–liquid feed fermentors. Methanogen colonized leaf biomass has been used as bio-film support to treat coffee processing wastewater as well as crop litter alternately in a year. During summer it functions as a biomass based biogas plants operating in the three-zone mode while in winter, feeding biomass is suspended and high strength coffee processing wastewater is let into the fermentor achieving over 90% BOD reduction.

Indian rules governing MSW treatment permit only biological methods such as composting or biomethanation for the fermentable fraction. While large cities in India have access to sophisticated fermentation technologies, small towns in the range of 50,000–500,000 population resulting in USW collection in the range of 10–100 t/day (available component 5–50 tons) do not have access to a viable technology. Usually these urban local bodies are cash starved and find it difficult to find finances for collection and processing. Conversion to biogas (for sale), compost or vermicompost provides good revenues that can match the collection and operating costs. Pilot plants of 1–2 t/day have been built in three towns and preliminary trials were encouraging [70].

4.3. Chemical transformation—bio-diesel from various sources

A diesel fuel has an essential function in the industrial economy of a developing country and is used in transports, industrial and agricultural goods, etc. Compared to the rest of the world, India's demand for diesel fuels is six times that of gasoline. The consumption of diesel fuels in India in 1994–1995 was 28.30 million tonnes of diesel [71] and 47.56 million tonnes of diesel in 2006–2007, which was 39.8% of the total consumption of petroleum products [3]. Economic growth is always accompanied by commensurate increase in the transport. This has stimulated the recent interest in alternative sources for petroleum-based fuels. An alternative fuel should be easily available, environment friendly and techno-economically competitive. One of such fuels is triglycerides and their derivatives. Vegetable oils, being renewable, are widely available from a variety of sources and have low sulphur contents close to zero and hence cause less environmental damage (lower green house effect) than diesel. Chemically the oils consist of triglyceride molecules of three long chain fatty acids that are ester bonded to a single glycerol molecule. These fatty acids differ by the length of carbon chain, orientation and position of double bonds in these chains. Thus bio-diesel refers to lower alkyl esters of long chain fatty acids, which are synthesized either by transesterification with lower alcohols or by esterification of fatty acids.

The use of vegetable oils, such as soya-bean, palm, sunflower, peanut and olive oil as alternative fuel has been around for 100 years when the inventor of the diesel engine Rudolph Diesel first tested peanut oil, in his compression ignition engine [72,73]. Different countries are looking for different types of vegetable oils as substitutes for diesel fuels that depending upon the climate and soil conditions [74]. For example, soya-bean oil in U.S., rapeseed and sunflower oils in Europe, palm oil in Southeast Asia and coconut oil in Philippines are being used. The use of vegetable oils as sources of diesel would require more efforts to increase the production of oil seed and to develop new and more productive plant species with high yield of oil, besides, some species of plants yielding non-edible oils.

The planning commission of India has launched a bio-fuel project in 200 districts of the 18 states in India. It has recommended two plant species viz. Jatropha (*Jatropha curcas*) and Karanj (*Pungamia pinnata*) for bio-diesel production [75,76]. Both these plants may be grown on a massive scale on agricultural/degraded/waste lands, so that the chief resource may be available

to produce bio-diesel on 'farm scale'. Vegetable oils occupy a prominent position in the development of alternative fuels although, there have been many problems associated with using it directly in diesel engine. These include interference of high viscosity of vegetable oil with the injection process leading to poor fuel atomization, inefficient mixing of oil with air resulting in incomplete combustion and high smoke emission, lube oil dilution, high carbon deposits, ring sticking, scuffing of the engine liner, and Injection nozzle failure. On the other hand, high flash point attributes to lower volatility characteristics. Their inability to be classified into types and grade of oil and local climatic conditions are the other factors for their unsuitability. For these triglycerides, both cloud and pour points are significantly higher than that of diesel fuel. These high values may cause problems during cold weather. These problems are associated with large triglycerides molecule and its higher molecular mass, which is avoided by chemically modified to vegetable oil in to bio-diesel that is similar in characteristics of diesel fuel [77–79].

The answer to these problems was found in chemical conversion of these triglycerides or vegetable oils were found in their chemical conversion to the bio-diesel by transesterification. The transesterification is an important process to produce the cleaner and environmentally safe fuel from vegetable oils. Bio-diesel is defined as the mono alkyl esters of long chain fatty acids derived from renewable feed stock, such as vegetable oil or animal fats, for use in compression ignition engines [73]. Bio-diesel which is considered as a possible substitute of conventional diesel fuel is commonly composed of fatty acid methyl/ethyl esters, obtained from triglycerides by transesterification with methanol/ethanol respectively. Bio-diesel is compatible with conventional diesel and both can be blended in any proportion. The typical characteristics of the bio-diesel are listed in Table 8.

In continued efforts for increasing economic viability of generating bio-diesels from various edible, non-edible and waste oils; a new concept has gained the momentum in recent past. This is production of bio-diesel from algae [17,18,20,80,81]. Earlier studies on liquid fuel from microalgae had begun in mid-1980s. During the world war II, although some German scientists attempted to extract lipids from diatom in order to resolve energy crisis [82], and soon later in the USA, research was conducted by a group of scientists at the Carnegie Institution of Washington, and their experiences had been summarized in a book [83] entitled "Algal Culture from Laboratory to Pilot Plant", but the technologies of making microalgae as fuels had not been fully exploited. The reasons could be as follows. First reason is that microalgae are less known source of lipids than plants and animals. Second, the prices for most plant oils are relatively low and animal fats are even cheaper; therefore, processes for the microbial oils production have mainly focused on high-valued products that cannot be produced by plants, such as omega-3 polyunsaturated fatty acids [84].

Table 8
ASTM specifications for Biodiesel B-100 (ASTM D6751).

Property	ASTM method	Limits
Flash point	D93	130 °C (min)
Water and sediment	D2709	0.05 vol.% (max)
Kinematic viscosity (40 °C)	D445	1.9–6.0 mm^2/s
Sulfated ash	D874	0.02 mass% (max.)
Sulfur	D5453	0.05 mass% (max.)
Cu strip corrosion	D130	No. 3 (max.)
Cetane No.	D613	47 (min.)
Cloud point	D2500	
Carbon residue (100% sample)	D4530	0.05 mass% (max.)
Acid No.	D664	0.80 mg KOH/g (max.)
Free glycerine	D6584	0.02 mass% (max.)
Total glycerine	D6584	0.24 mass% (max.)
Phosphorous content	D4951	0.001 mass% (max.)
Distillation temperature, 90% recovery	D1160	360 °C (max.)

Khan et al. [17] has presented a critical evaluation on prospects of bio-diesel production microalgae. They have emphasized the need to explore the possibilities of producing bio-diesel from microalgae, as it will not compete with the land and cereal crops. In India, about 26 million hectare lands are used for the oilseed cultivation, mainly on non-irrigated marginal lands, dependent on monsoon rains, and with low levels of input usage. With the result, the yields of oilseeds cultivation are rather low at less than 1 t/ha [85]. On the other hand, in India, per capita consumption of edible oil is also growing steadily with steady growth in population and personal income. This is in spite of the fact that Indian vegetable oil economy is world's fourth largest after USA, China and Brazil. However, oilseeds output and in turn, vegetable oil production have been trailing consumption growth, necessitating imports to meet supply shortfall [85].

Therefore, for country like India, which already depends on the imports of vegetable oil, we have to see the other alternatives for economically viable production of bio-diesel. Since the demand for edible vegetable oil exceeds supply, the government decided to use non-edible oil from *J. curcas* oilseeds as bio-diesel feedstock. But the main problem in getting the bio-diesel programme rolling is the difficulty linked to initiating large-scale cultivation of Jatropha. Farmers do not yet consider Jatropha cultivation remunerative enough because the fruits appear after 3 years of crop plantation. For instance, sugarcane plantations yield 70 t/ha and fetch the farmer Rs. 70,000/ha at a sugarcane price of Rs. 1000/t. In comparison, the Jatropha farmer gets Rs. 5000/t of oilseeds and if the yield is 3.75 t/ha, his income will be only Rs. 18,750/ha [86]. The other main issue is the lack of seed collection and oil extraction infrastructure. In the absence of this infrastructure and available oilseeds, it will be difficult to persuade entrepreneurs to install transesterification plants.

In view of the above, whether being edible oil or non-edible oil, we are not getting the viable alternative of bio-diesel. There is an urgent need to design integrated energy farms that are capable of producing fuel and fertilizers besides foods and feed. These energy farms should be established on waste/barren lands and should need least resources like fresh water or chemical fertilizers. Today, the potential value of microalgal photosynthesis to produce bio-diesel is, however, widely recognized. Production of bio-diesel using microalgae biomass appears to be a viable alternative [87]. The oil productivity of many microalgae exceeds the best producing oil crops. Microalgae are photosynthetic microorganisms which convert sunlight, water and CO_2 to sugars, from which macromolecules, such as lipids and triacylglycerols (TAGs) can be obtained. These TAGs are the promising and sustainable feedstock for bio-diesel production. Microalgal bio-refinery approach can be used to reduce the cost of making microalgal bio-diesel. Microalgal-based carbon sequestration technologies cover the cost of carbon capture and sequestration. So, the road ahead for India is to see the viable option of algal farming.

5. Conclusions

A critical analysis of the potential of biomass conversion to energy has been presented. It is evident from the above discussions that a large potential lies for the exploitation of available biomass in India to convert it to energy. Large scope exists for the thermal conversion processes such as pyrolysis, liquefaction and biomass gasification for power generation in India. In view of the availability of waste biomass e.g. agricultural waste, food wastes, industrial wastewaters generated in large volumes, and MSW, anaerobic digestion is a promising route. A number of power

generation projects are already proved successful in India based on gasification based cogeneration rural electrification plants. These plants have not only solved the rural electrification problem for the remote villages, where infrastructural costs could have been quite high for conventional electrification, but also the power generation cost has also been relatively low. Production of bio-oils by fast pyrolysis also can be quite feasible, for power generation applications, with certain constraints, not very difficult to overcome.

If we talk of second generation fuels, the inherent competition with food crops, as well as GHG production due to land-use change and transportation of bio-crops to the bio-refineries, may pose some hurdles in the way of bio-diesel production. But it may not be difficult to overcome it with certain remedial measures such as setting bio-refineries in close vicinity of the bio-crop production fields. In present day scenario, non-edible oils also do not seem to offer very attractive options due to limited availability of marginal lands as well as less profitable venture for farmers. The solution may be found in the algae based bio-diesel production. With steady upward demand for the petroleum-based fuels, and constant increase in demand of electrical power generation, it seems that thermal conversion processes as well as cogeneration based gas power plants may emerge out as a solution to the energy problem of India.

References

[1] British Petroleum. BP statistics review of world energy, June; 2009, www.bp.com/statisticalreview.
[2] Planning Commission. Integrated energy policy—report of the expert committee, August; 2006, planningcommission.gov.in/reports/genrep/rep_intengy.pdf.
[3] Basic statistics on Indian Petroleum & Natural Gas. Ministry of Petroleum and Natural Gas, Economic Division; 2008–09, http://petroleum.nic.in/total.pdf.
[4] Nouni MR, Mullick SC, Kandpal TC. Providing electricity access to remote areas in rural India: an approach towards identifying potential areas for decentralized power supply. Renew Sust Energy Rev 2008;12:1187–220.
[5] Nouni MR, Mullick SC, Kandpal TC. Techno-economics of micro-hydro projects for decentralised power generation in India. Energy Policy 2006;34:1161–74.
[6] Buragohain B, Mahanta P, Moholkar Vijayanand S. Biomass gasification for decentralized power generation: the Indian perspective. Renew Sust Energy Rev 2010;14(January (1)):73–92.
[7] McKendry P. Energy production from biomass (part 1): overview of biomass. Bioresour Technol 2002;83:37–46.
[8] Avis M. Biofuels—fuelling the world or fooling the world? Folkcenter Trainee.. Nordic Folkecenter for Renewable Energy, January; 2008 , http://www.folkecenter.net/gb/rd/transport/plant_oil/biofuels/.
[9] http://www.bioenergywiki.net/Main_Page.
[10] John J. Bio-fuel drive looses stream. Indian Express 2008;16(September).
[11] Jatropha World, http://www.jatrophabiodiesel.org/jatrophaPlantation.php.
[12] Agrofuels—fuelling or fooling the Europe? Friends of the Earth's position on the use of plant-based fuels in transport, February;. 2008, http://www.foe.co.uk/resource/briefings/fuelling_or_fooling_europe.pdf.
[13] http://www.foe.co.uk/resource/briefings/agrofuels_fuelling_or_fool.pdf.
[14] Davies E. The biofuel future?In: Chemistry World; April 2009. p. 40–43.
[15] Grain. Jatropha—the agrofuel of the poor? Seedling 2007;(July):34–5. http://www.grain.org/seedling_files/seed-07-07-en.pdf.
[16] Sanderson K. Wonder weed plans fail to flourish. Nature 2009;461(September):328–9.
[17] Rashmi KSA, Hussain Mir Z, Prasad S, Banerjee UC. Prospects of biodiesel production from microalgae in India. Renew Sust Energy Rev 2009;13:2361–72.
[18] Huang GH, Chen F, Wei D, Zhang XW, Chen G. Biodiesel production by microalgae technology. Appl Energy 2009.
[19] Powell EE, Hill GA. Economic assessment of an integrated bioethanol–biodiesel–microbial fuel cess facility utilizing yeast and photosynthetic algae. Chem Eng Res Des 2009;87:1340–8.
[20] Mata Teresa M, Martins Antonio A, Caetano Nidia S. Microalgae for biodiesel production and other applications: a review. Renew Sust Energy Rev 2010;14:217–32.
[21] Li Y, Wang B, Wu N, Lan CQ. Effect of nitrogen sources on cell growth an lipid production of *Neochloris oleoabundans*. Appl Microbiol Biotechnol 2008;81(4): 629–36.
[22] Li Y, Horseman M, Wu N, Lan CQ, Dubois-Clero N. Biofuels from microalgae. Biotechnol Progress 2008;24(4):815–20.
[23] Richmond A. Handbook of microalgal culture: biotechnology and applied phycology. Blackwell Science Ltd.; 2004.
[24] Ravindranath NH, Hall DO. Biomass energy and environment: a developing country prospective from India. Oxford: Oxford University Press; 1995.
[25] Ravindranath NH, Somashekar HI, Nagaraja MS, Sudha P, Sangeetha G, Bhattacharya SC, et al. Assessment of non-plantation biomass resources potential for energy in India. Biomass Bioenergy 2005;29:178–90.
[26] Smith KR. Fuel combustion, air pollution exposure and health: the situation in developing countries. Annu Rev Energy Environ 1993;18:529–56.
[27] Bhattacharya SC, Jana C. Renewable energy in India: historical developments and prospects. Energy 2009;34:981–91.
[28] Demirbas A. Biofuels securing the planet's future energy needs. Energy Conversion Manage 2009;50:2239–49.
[29] Ravindranath NH, Balachandra P. Sustainable bioenergy for India: a technical, economic and policy analysis. Energy 2009;34:1003–13.
[30] Somashekhar SP, Rao S, Ravindranath NH. Sustainable biomass production for energy in India. Biomass Bioenergy 2003;25:501–15.
[31] Planning Commission of India, Working paper on 'Leasing of degraded forest land; Report Reprint Series No. 1/99-PC http://planningcommission.nic.in/reports/wrkpapers/wp_lease.pdf.
[32] Kapoor RPA, Agarwal, editors. The price of forests. New Delhi: Centre for Science and Environment; 1992. p. 173.
[33] Handbook of statistics: section A, Table 03. India: Ministry of Agriculture; 1996–97, http://dacnet.nic.in/rice/HS-A-Table-03.htm.
[34] Sudha P. Plantation forestry; land availability and bio-mass production potential in Asia. Report submitted to ARPEEC, Sida, Energy Program, AIT, Bangkok; 1996.
[35] NRSA Report on area statistics of land use/land cover generated using remote sensing techniques. Hyderabad: Department of Space; 1995.
[36] CMIE. Directory of Indian agriculture, Mumbai, India; 1997.
[37] CES. Annual report. Bangalore: Centre for Ecological Sciences, IISc; 1995.
[38] Indian Biomass Atlas http://lab.cgpl.iisc.ernet.in/Atlas/Atlas.aspx.
[39] Singh Y. Waste biomass to energy, environment and waste management; 1 October; 2008, www.wealthywaste.com/waste-biomass-to-energy.
[40] MNRE annual report 2008–09. New Delhi: Ministry of New and Renewable Energy; 2008–09.
[41] Kansal A, Rajeshwari KV, Balakrishnan M, Lata K, Kishore VVN. Anaerobic digestion technologies for energy recovery from industrial wastewater—a study in Indian context. TERI information monitor on environmental science 1998;3(2):67–75.
[42] Singh SP, Pandey P. Review of recent advances in anaerobic packed-bed biogas reactors. Renew Sust Energy Rev 2009;13:1569–75.
[43] Zafar S. Waste to energy conversion—a global perspective; EARTHTOYS The renewable energy emagzine; August 2008.
[44] Zafar S. Biomass wastes, alternative energy eMagzine—AltEnergyMag.com; August/September 2009.
[45] Rowell RM. The chemistry of solid wood. Washington, DC: American Chemical Society; 1984.
[46] Appel HR, Fu YC, Friedman S, Yavorsky PM, Wender I. Converting organic wastes to oil. US Burea of Mines Report of Investigation No. 7560; 1971.
[47] Katyal S. Effect of carbonization temperature on combustion reactivity of bagasse char. Energy Sources Part A 2007;29:1477–85.
[48] Mohan D, Pittman Jr CU, Steele PH. Pyrolysis of wood/biomass for bio-oil: a critical review. Energy Fuels 2006;20:848–89.
[49] Demirbas A. Producing bio-oil from olive cake by fast pyrolysis. Energy Sources Part A 2008;30:38–44.
[50] Demirbas A. Biorefineries: current activities and future developments. Energy Conversion Manage 2009;50:2782–801.
[51] Ganesh A, Banerjee R. Biomass pyrolysis for power generation—a potential technology. Renew Energy 2001;22:9–14.
[52] Abe H. Summary of biomass power generation in India; a case study report prepared for Japan. International Cooperation Agency (JICA); 2005 , http://gasifiers.bioenergylists.org/gasdoc/abe/IndiaBioSummary050721Web.pdf.
[53] Hiremath RB, Kumar B, Balachandra P, Ravindranath NH, Raghunandan BN. Decentralized renewable energy: scope, relevance and applications in the Indian context. Energy Sustain Dev 2008;13:4–10.
[54] Chanakya HN, Reddy BVV, Modak J. Biomethanation of herbaceous biomass residues using 3-zone plug flow like digesters—a case study from India. Renew Energy 2009;34:416–20.
[55] Bhat PR, Chanakya HN, Ravindranath NH. Biogas plant dissemination: success story of Sirsi, India. Energy Sustain Dev 2001;V(March (1)):39–41.
[56] Reddy AKN. The blessing of the commons. Energy Sustain Dev 1995;II(1):48–50.
[57] Goldemberg J, Johansson TB, Reddy AKN, Williams RH. A global clean cooking fuel initiative. Energy Sustain Dev 2004;VIII(3):5–12.
[58] Reddy AKN. Rural energy consumption pattern—a field study—analysis of results. Biomass Bioenergy 1982;2(4):255–80.
[59] Srivastava RC, Pillai KR, Singh HD, Raghavan KV. Studies in design of anaerobic digester for water hyacinth. In: Proceedings of III international conference on water hyacinth; 1985. p. 566–92.
[60] Hobson PN, Bousefield R, Summers R. Methane production from agricultural and domestic wastes. London: Applied Science Publishers Ltd.; 1981. p. 121.
[61] Kale SP. Nisarghruna plant for urban and rural waste management, energy conservation, better environment and restoration of soil fertility. Bioenergy News 2004;8(1):1–5.
[62] Andersson J, Bjornsson L. Evaluation of straw as a biofilm carrier in the methanogenic stage of two-stage anaerobic digestion of crop residues. Bioresour Technol 2002;85:51–6.

[63] Das CR, Ghatnekar P. Replacement of cowdung by fermentation of aquatic and terrestrial plants for use as fuel, fertilizer and biogas plant feed. In: TERI Technical Report. TERI; December; 1979.
[64] Kalia AK, Kanwar SS. Biogas generation from Ageratum in a semi-continuous plant. SESI J 1995;5(2):61–8.
[65] Sharma A, Unni BG, Singh HD. A novel fed batch system for biomethanation of plant biomasses. J Biosci Bioeng 1999;87(5):678–82.
[66] Jagadish KS, Chanakya HN. Further studies in biogas technology. In: ASTRA Technical Report. Bangalore: Indian Institute of Science; 1987.
[67] Jagadish KS, Chanakya HN. Final report on project biogas production from leaf biomass. In: ASTRA Technical Report. Bangalore: Indian Institute of Science; 1999.
[68] Rajabapaiah P. Personal communication; 2005.
[69] Reddy AKN, Krishnaswamy KN. Innovation chain under the impact of technology imports. Lecture 3(a), R&D Management Course of Department of Management Studies. Bangalore: Indian Institute of Science; 1988, February 22.
[70] Technology Informatics Design Endeavour (TIDE). Bioreactor for treatment of organic fraction of urban municipal waste at Siraguppa. In: TIDE Technical Report. Bangalore: Technology Informatics Design Endeavour; 2005.
[71] Ministry of non-conventional energy sources (MNES) and planning commission; 2002.
[72] Shay EG. Diesel fuel from vegetable oils: status and opportunities. Biomass Bioenergy 1993;4:227–42.
[73] Krawezy T. Biodiesel—alternative fuel makes in roads but hurdles remain. INFORM 1996;7(8):800–15.
[74] Demirbas MF. Biorefineries for biofuel upgrading: a critical review. Appl Energy 2009;86:S151–61.
[75] Subba Rao Dr IV. General President Indian Science Congress Association. ''Presidential address'' 93rd Indian science congress annual report; 2005–06. p. 12.
[76] Abdul Kalam Dr APJ. Hon'ble President of India ''Dynamics of Rural Development'' 93rd Indian science congress annual report; 2005–06. p. 34.
[77] Barnwal BK, Sharma MP. Alternate Hydro Energy Center, IIT Roorkee. Prospect of Bio Diesel Production from Vegetable Oils in India. Renew Sust Energy Rev 2005;9:363–78.
[78] Sundarapandian S, Devaradjane G. Department of Automobile Engineering MIT-Chrompet, Experimental Investigation of the Performance on Vegetable Oil Operated C.I Engine. 19th National Conference on I.C Engine and Combustion. December 21–23, 2005 Annamalai University, Chidambaram. p. 87–94.
[79] Murugesan A, Umarani C, Chinnusamy TR, Krishnan M, Subramanian R, Neduzchezhain N. Production and analysis of bio-diesel from non-edible oils—A review. Renew Sust Energy Rev 2009;13:825–34.
[80] Singh SP, Singh D. Biodiesel production through the use of different sources and characterization of oils and their esters as substitute of diesel, a review. Renew Sust Energy Rev 2010;14:200–16.
[81] Chishti Y. Biodiesel from algae. Biotechnol Adv 2007;25:294–306.
[82] Cohen Z, Norman HA, Heimer YM. Microalgae as a source of x-3 fatty acids. World Rev Nutr Diet 1995;77:1–31.
[83] Burlew JS, editor. Algal culture from laboratory to pilot plant. Washington (DC): Carnegie Institution of Washington Publication; 1953. p. 600.
[84] Wen ZY, Chen F. Optimization of nitrogen sources for heterotrophic production of eicosapentaenoic acid by the diatom *Nitzschia laevis*. Enzyme Microbiol Technol 2000;29:341–7.
[85] Mehta BV. Overview of the Indian oilseed sector and demand of edible Oils. In: Paper presented at Exchange Traded Commodities Outlook; 2005–06.
[86] Gonsalves JB. An assessment of the biofuels industry in India: Report. United Nations conference on trade and development 2006; UNCTAD/DITC/TED/2006/6.
[87] Sharma YC, Singh B. Development of biodiesel: current scenario. Renew Sust Energy Rev 2009;13:1646–51.